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ABSTRACT

This paper presents the results of a statistically designed experiment with eight all-refrigerator cabinets. The cabinets were designed with a view to be identical except for the fact that each cabinet was fitted with a specific non-adiabatic capillary arrangement. These cabinets were tested to the New Zealand test standard (NZS 6205.2) at 32°C ambient temperature and then the tests were repeated at 10°C to study the effect of low ambients on the refrigerator performance. The effect of capillary tube variations has been investigated with respect to power consumption, the stability of the compressor cycle and the refrigerant subcooling in refrigerators.

Key Words: Capillary tube, adiabatic, non-adiabatic, refrigerator, freezer

INTRODUCTION

Every vapour compression refrigeration system has an expansion device to meter the refrigerant flow from the high pressure (condenser side) to the low pressure (evaporator side). Capillaries are commonly used in small refrigeration systems (eg. household refrigerators and freezers, dehumidifiers and room air-conditioners) due to their simplicity and low cost. It is simply a long hollow tube of drawn copper with an inside diameter ranging from 0.33 mm to 1.5 mm and length from 2 to 5 m, connecting the high side to the low side. Capillaries can be of two types namely, the adiabatic and the non-adiabatic. In the former, the refrigerant expands from high pressure to low pressure adiabatically (ie. tube is fully insulated) while in the latter, the refrigerant expands to low pressure in the capillary tube which is set up to form a heat exchange relationship with the suction line. Non-adiabatic capillaries are normally used in household refrigeration systems. In practice, the capillary is soldered to the suction line or run inside the suction line to superheat the suction gas to ambient temperature as shown in Figure 1. This heat transfer decreases the enthalpy at the evaporator inlet and thus increases the heat available from evaporation, and the efficiency of the refrigerator.

Traditionally, capillary tubes were designed for CFC-12 as working fluid in household refrigerators and freezers. With the change to HFC-134a, it has been shown (Behrens et al (1989)) that both capillary length and the amount of subcooling for optimum performance must increase over systems optimised for CFC-12. Since the heat exchanger effectively alters both these parameters in a rather complex manner, this experiment was set up with production refrigerators (with relatively simple systems) and in a manner that could measure complex relationships. Energy consumption was the primary output of this experiment, while system stability and system temperatures were also measured. There is also some evidence that subcooled capillary systems can be unstable (ASHRAE (1994)) and that the location of the capillary/suction line heat exchanger can affect this instability. This instability is seen in a refrigerator in the form of erratic run times, when consecutive compressor cycles are 50 to 100% longer (or shorter) than the subsequent cycles. These erratic run times have been known for a long time to be a function of the position of the heat exchanger along the capillary for CFC-12 (ASHRAE (1994)). Therefore, the objective of this paper is to study the effect of capillary and heat exchanger variations on power consumption and cycle stability of eight 270 litre all-refrigerators, made on the production line. All these cabinets were charged with HFC-134a as refrigerant and had cyclo-pentane blown polyurethane as insulant.

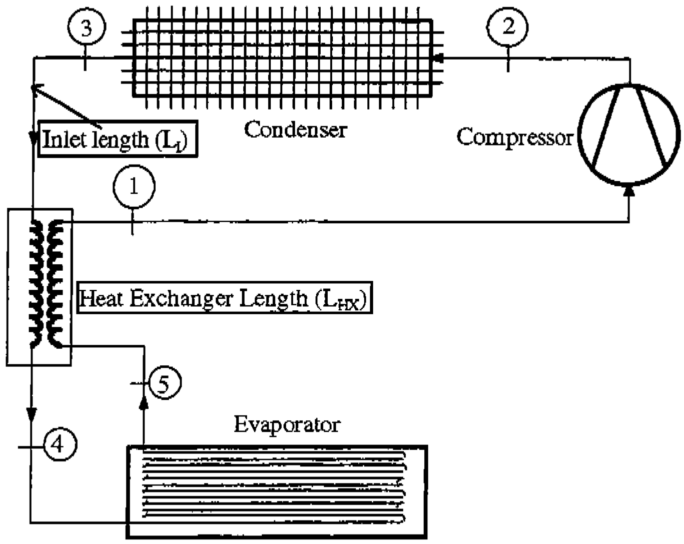

Figure 1. Schematics of a household refrigeration system with non-adiabatic capillary tube.

EXPERIMENTAL SET UP

An all-refrigerator is a cabinet designed for the refrigerated storage of food at temperatures above 0 °C, has a source of refrigeration, and is intended for household use. It may include a compartment with a small volume for freezing and storage of ice. The study used a statistically designed experiment plan where eight refrigerators were specifically built with eight different capillary arrangements (see Table 1). The capillary length is divided into three parts : the inlet length (L_I) connecting the condenser with the heat exchanger, the heat exchange length (L_{HX}), and the final length between the heat exchanger and the evaporator (see Figure 1). Therefore, the capillary variables in this investigation include the following :

1. Total length (L) = 3,500 mm and 2,500 mm (both of 0.66 diameter)
2. Inlet length (L_I) = 300 mm and 500 mm, and
3. Heat exchange length (L_{HX}) = 1,200 mm and 1,950 mm.

Table 1 : Experimental plan showing the randomised order of testing and the basic results

Cabinet	VARIABLES			RESULTS					
	Length (mm)			Cycle stability (standard deviation in minutes)		Subcooling (K)		Power (Wh/day)	
	Cap (L)	HX (L_{HX})	Inlet (L_I)	@ 10°C	@ 32°C	@ 10°C	@ 32°C	@ 10 °C	@ 32 °C
G	2500	1200	300	23	43	-	-	656	1482
B	3500	1200	300	41	6	-	-	676	1528
C	2500	1950	300	10	10	6	0	654	1560
F	3500	1950	300	26	9	13	7	595	1379
E	2500	1200	500	6	4	1	3	667	1457
D	3500	1200	500	12	5	-	-	658	1471
A	2500	1950	500	9	8	5	0	611	1382
H	3500	1950	500	6	5	7	6	705	1620

For details, see 'Results and discussion' section.

The cabinets were tested to New Zealand Standard NZS6205.2 [1989] which is a closed door power use test at 32°C ambient temperature with no requirement of ambient relative humidity. The tests were then repeated at 10°C ambient temperatures to check the effect of low ambients on the refrigerator performance.

PROCEDURE

Eight cabinets were assembled and were initially charged with approximately 80% of the standard HFC-134a quantity. The charging fittings were left on to add refrigerant later. Each cabinet was run for about 16 hours in a stable ambient (of 20 °C) with the control tube removed to enable the refrigerator to run continuously. The refrigerant was added in 5g increments until the evaporator inlet and outlet temperatures were the same. Thus, each refrigerator had a similarly flooded evaporator. The cabinets were then tested to NZS 6205.2[1989] at two different ambient temperatures of 32 °C and 10 °C respectively. The temperatures were recorded at eight locations over and above the three locations required by NZS 6205.2. Subsequently, the energy consumption of each cabinet was recorded with a watt-hour transducer using a Labview data logging system. Because of the expected large random variation in refrigerator performance (mostly due to compressor variation) combined with the need to measure complex interactions, the statistically designed (or multivariable) experimental plan was chosen as explained below.

STATISTICALLY DESIGNED EXPERIMENTS

Statistically designed experiments were developed in the 1930s by Fisher (1935) to analyse agricultural experiments where they had very little control of Plot fertility, rainfall and sunlight. A more modern text is "Statistics for Experimenters" by Box et al (1978). These experiments have two significant advantages. They average the effects of all the results to give less experimental error and measure the complex effects of multiplicative interactions. A multiplicative effect is one where the response to two variables is much greater (or much less) than the sum of the responses of each variable acting alone (ie when the other variables are held constant).

In this case there were four variables each with two levels to give 2^4 or 16 combinations (usually described as a 2^4 experiment) that are shown in Table I. The experimental order is then randomised to minimise any temporal effects (this experiment was randomised before the cabinets were labelled so the random order was A,B,C etc). The effects of each variable are calculated by subtracting the average of the 8 results at the high value from those at the low value of that variable. A "t test" is then utilised to check the statistical significance ('t' test determines the probability that a result is due to a genuine effect rather than due to random variability).

ERRORS

The energy label regulations require that up to three refrigerators be tested, and that their average power consumption is printed on the energy labels registered with the authorities and shown on the cabinets. In this analysis, we have used the standard deviation of Fisher & Paykel's most recent results to estimate the experimental error for power consumption. The standard deviation of these 1994 tests was 83Wh/day or an error of plus/minus 163Wh/day. However as the designed experiment averages 8 results, the error in the effects of each variable is reduced to 58Wh/day (= $163/\sqrt{8}$) as shown in Table 2. The error in cycling variability can be estimated from the experiment itself by assuming that all the effects, other than the average, smaller than 12 are manifestations of random variability. Thus an error of plus/minus 9 minutes can be estimated by taking the square root of the sum of the squares of these small effects.

RESULTS AND DISCUSSION

The basic data are shown in Table I. The first column shows the randomised order of the testing (see Statistically Designed Experiments Section above). The second, third and fourth columns show the variables arranged in the "standard order" of designed experimentation. The cycling stability columns show the standard deviation of the compressor cycle time where a large standard deviation implies very erratic and unstable cycling while a small standard deviation implies stable cycling. The subcooling columns show the difference between the condensing temperature and the capillary inlet temperature of the refrigerant. The blank spaces are due to thermocouples failing during the foaming process. The last two columns show the power consumed when cabinets were tested to NZS6505.2[1989] at 32 °C and 10 °C respectively. The power consumption data for all the eight cabinets is plotted in Figure 2 for both the 32 °C and the 10 °C ambient tests along with an additional plot of 10 °C results multiplied by 2.27. It is interesting to note from the Figure how consistently the power consumption by a refrigerator at 32 °C ambient temperature is 2.27 times higher than the corresponding power consumption of the same cabinet when tested at 10°C ambient temperature. It has been observed from the experimental data that there was no correlation between power consumption and the refrigerant subcooling (at the capillary inlet), refrigerant temperature at capillary inlet (ie. filter) or the refrigerant temperature at the suction line outlet.

Further results of the experimental analysis are shown in Table II where the first column lists capillary variables and combination of variables that induce the effects shown in other columns. The effect on power consumption is shown in the fifth column followed by the error value at 32 °C in the last column. The power effects of 10 °C testing are not shown as they were very similar to 32 °C and we were unable to estimate the error.

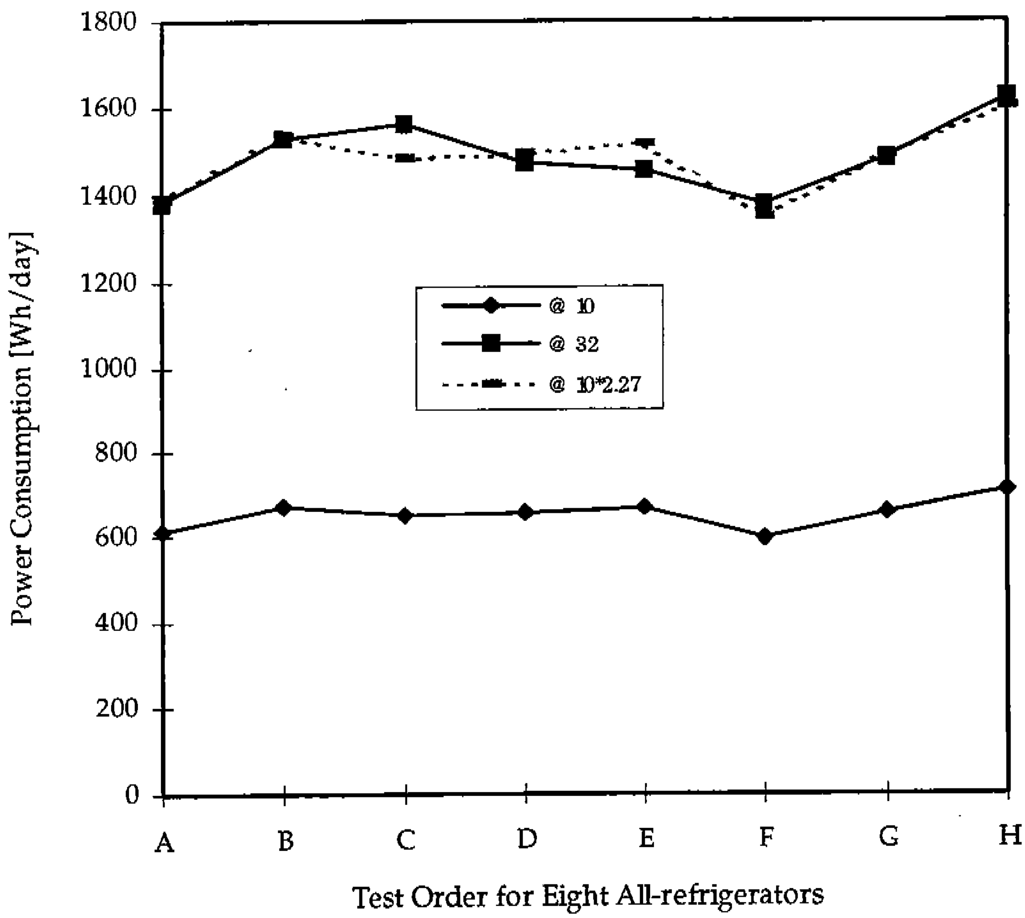

Figure 2 : Variation of power consumption for the eight cabinets tested to NZS6205.2[1989] at two different ambients of 32 °C and 10 °C respectively.

The three values with an asterisk were the only effects that were statistically significant at the 90% confidence level (ie. there is a less than 10% probability that they were due to experimental error). The average values of the cycle stability show that there is more stability at 32°C. The significant result at 10 °C is that the cycling stability is improved by 17 minute (compared to 12 minute at 32 °C) when the inlet length is increased from 300mm to 500mm.

TABLE II : Effect of capillary tube variables on power consumption and cycle stability

Variables	Cycle stability (standard deviation in minutes)			Power (Wh/day)	
	@ 10 °C	@ 32 °C	Error	@ 32 °C	Error
Average	17	11	9	1485	58
Cap length (L)	9	-10	9	29	58
HX length (L_{HX})	-8	-7	9	1	58
Cap length*HX length (= $L*L_{HX}$)	-3	8	9	-1	58
Inlet length (L_I)	-17.0*	-12	9	-5	58
Cap length*Inlet length (= $L*L_I$)	-8	9	9	97.0*	58
HX length*Inlet length (= $L_{HX}*L_I$)	6	9	9	36	58
Cap length*HX length*Inlet length (= $L*L_{HX}*L_I$)	-2	-10	9	113.0*	58

* shows that the result is statistically significant.

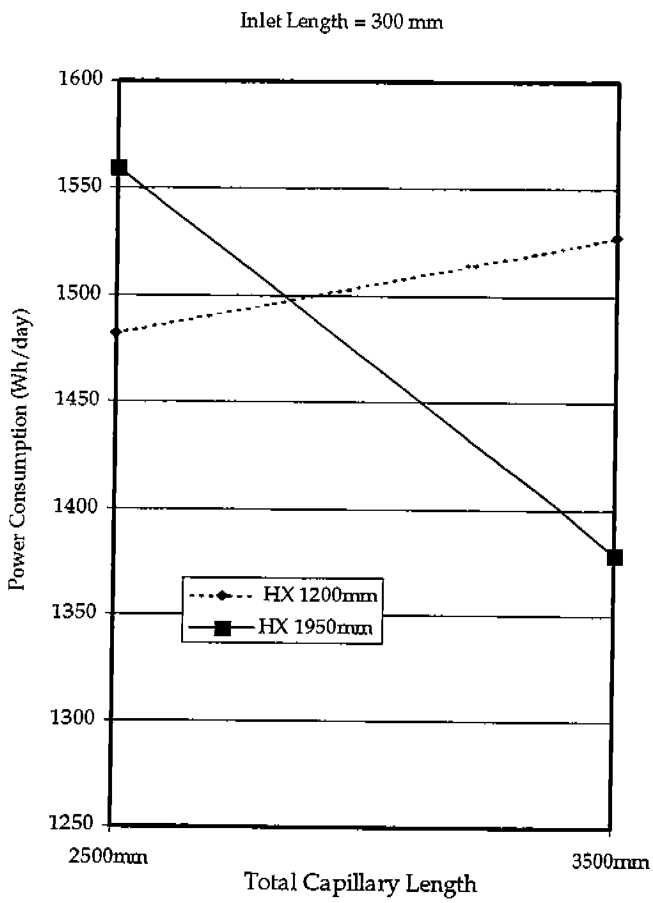

Figure 3 : Effect of capillary tube variation on power consumption at 32°C ambient testing

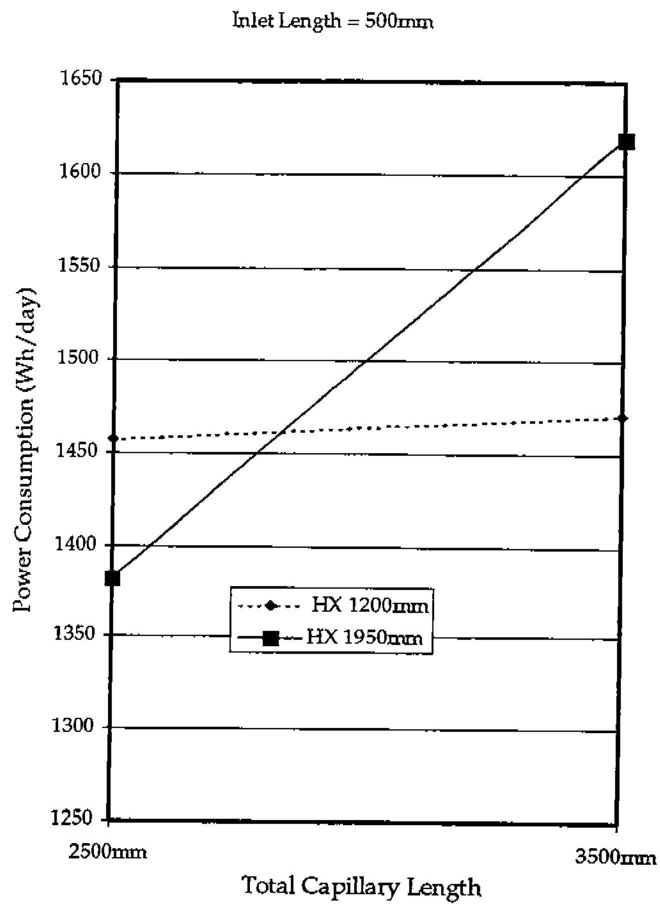

Figure 4 : Effect of capillary tube variation on power consumption at 32°C ambient testing

The power effects are minimal for the three main variables and two of the interactions. As is discussed earlier, the three variables in the capillary arrangements are the total capillary length (L), the inlet length (L_I) and the heat exchanger length (L_{HX}). The main effects of these variables are either very small or are masked by the experimental error. The two significant power effects of 97W and 113W are due to the $L*L_I$ and $L*L_I*L_{HX}$ interactions. These interactions are illustrated in Figures 3 and 4 for 32°C ambient case where power consumption (Wh/day) is plotted as a function of capillary total length (L) for inlet capillary lengths (L_I) of 300 mm and 500 mm respectively. Both the figures show the power consumption for two heat exchanger lengths (L_{HX} = 1200 mm and 1950 mm). It is interesting to note from these figures that a lower power consumption results from the combination of a long heat exchanger length with either a long capillary (L = 3500 mm) and short inlet (L_I = 300 mm) or a short capillary (L = 2500 mm) and a longer inlet (L_I = 500 mm). As is mentioned above, our observation of experimental data has revealed that the power consumptions were not due to any temperature effects and therefore, we can conclude here that these results are independent of temperature effects and are strongly dependent on capillary arrangement. Viewing again Figures 3 and 4 closely, it is apparent that for the lengths studied in this investigation, a longer heat exchanger (ie. L_{HX} = 1950 mm) mostly results in lower power consumption. The cycling variability at 10 °C is affected only by the inlet length (L_I) while at 32 °C, all the effects are masked by the error.

CONCLUSIONS

From this statistical experiment, it may be concluded that the capillary total length (L), heat exchanger length (L_{HX}), and capillary inlet length (L_I) have little effect on power consumption. This result showing that capillary length and heat exchange length (acting alone) having no significant effect is counter intuitive. Nonetheless, the range of lengths tested is within the variation seen between various manufacturers, and the industry has known for a long time that large variations in capillary length (on the same cabinet) have no effect on power consumption (Spong [1996]). However, they interact together to give significant improvements in power consumption. Thus a short capillary inlet length (L_I) combined with a long capillary (L) and long heat exchanger (L_{HX}), gives the best result with the "opposite combination", long inlet, short capillary and long heat exchanger giving the next best result. Further, there are no obvious correlations between any of the measured temperatures and the power consumptions. Lastly, the power consumption at 32 °C is about 2.3 times greater than that at 10°C. The cycling stability is worse at 10 °C ambient and tends to confirm the predictions in the literature that short capillary inlet lengths are unstable.

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